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Transformation of soil and land resources of the Middle Siberia in the conditions of climatic changes

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Abstract. The paper describes the fields of transformation of soil and land resources of the Middle Siberia as the result of long-term climatic changes. The description of soil and land resources is given. The climatic changes have been evaluated for the period from 1919 to 2018, and increase of the annual mean air temperature and amount of precipitation in natural zones of the region has been established on the basis of the analysis of linear trends. Under the impact of these factors, shifting of zone borders occurs, which leads to replacement of the soil cover structure at the species, generic and subtype levels. Changing regimes and soil properties cause the necessity to use new sorts and adapted technologies for crop growing.

1. Introduction

The soil and land resources are the most consumed part of the environment, the economic load on which is continuously growing, and, which is specifically important, land resources represent a spatial warranty of normal life and activity of the present and future generations.

Climatic conditions, the long-term change of which defines soil formation processes and formation of specific soil types as a result, is one of the main soil forming factors. Global and regional soil and geographical regularities are associated with the climate. Significant climate changes have been noted in the recent decades, and the question of the reasons for them requires studying [1]. A possible reason for rhythmical planetary climate change is a combination of natural processes of the earth (oceanic currents, volcanism, atmospheric circulation) and satellite (change of orbital parameters of the earth, solar activity) origin. During the recent 200–250 years these processes have been accelerated significantly by human activity causing increase of greenhouse gases concentration, primarily CO₂, in the atmosphere. Understanding of the processes causing climate change, the orientation of its main trends allows predicting possible consequences, risks and benefits.

The current climate studies and data of model calculations show that in Russia, in Siberia in particular, the tendency to global warming is more distinct as compared to other regions of the globe. In the recent 100 years (1907–2006), warming in general in Russia made 1.29 °C according to the data of



the Federal Service for Hydrometeorology and Environmental Monitoring in Russia, and it makes 0.74 °C as per the data of the Intergovernmental Panel on Climate Change, IPCC (figure 1) [2].

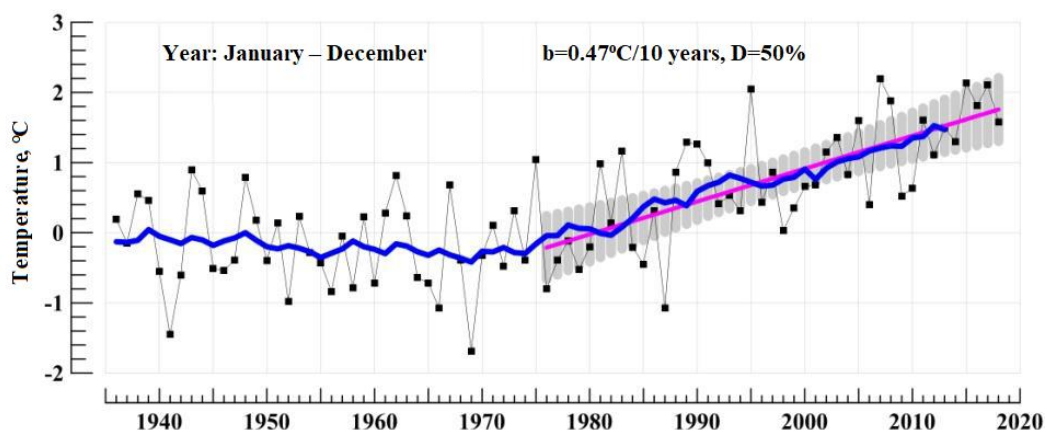


Figure 1. Change of annual mean air temperature averaged for area of Russia in deviations from average values for 1961–1990 (11-years’ sliding average, linear trend for 1976–2018 with a 95% confidence band are indicated; b is trend coefficient (°C/10 years), and $D\%$ is trend contribution to total dispersion) [2].

According to the general summary of the evaluation report of the IPCC, the temperature of the surface air in 1967–2006 in Russia grew by 1.33 °C (figure). This tendency is reflected in factor and soil formation processes change.

The purpose of the study was to identify transformations of soil and land resources of the Middle Siberia in climate change conditions.

2. Research task setting and results

The total area of the Krasnoyarsk Territory is 233.97 mln ha (13.7 % of the area of the Russian Federation). According to the Soil Map of the RSFSR, scale 1:2,500,000 [3], the share of the soil cover is 24.14 mln ha, which is 95.8% of the area of the region. The non-soil formations make 9.83 mln ha (4.2%), including stone placers — 5.85, loose rocks — 0.47, glaciers — 1.87, and water — 1.64 mln ha. The areas of soils and non-soil formations have been defined with the use of the materials of scientific monographs [4, 5] and the Unified State Register of Soil Resources of Russia compiled in 2013 by the V.V. Dokuchayev Soil Institute [6].

The following soils prevail in the structure of the soil cover (% of the total area of the territory): tundra and taiga podburs — 17.2, arctic and arctic tundra and their complexes — 12.8, cryozems and their combinations with pale cryozems, cryopeat and pale — 10.0, tundra gley and their complexes — 7.7, taiga gley — 6.1, sod-podzol and their varieties — 5.6, brown-taiga — 5.6, sod-carbonate and humus-carbonate — 5.0, podzols — 4.5, floodplain — 3.4, grey forest and their varieties — 3.0, peat boggy — 2.5, granuzems — 2.4, sod-taiga — 2.3, black soil and meadow-black soil — about 2.0%. In total, these soils make over 90.0% of the area of the territory and 94.2% of the soil cover. The area of the remaining soils (humus-carbonate tundra, peat-podzol-gley, mountain primitive) varies from 1.0 to 1.6%. Mountain soils in the soil cover structure occupy almost 35%, and the area under forest soils is 108.86 mln ha or 48.5% of the soil cover.

The Krasnoyarsk Territory is one of the largest food producers in the east of Russia. The region takes the 2nd place in the Siberian Federal District in terms of agricultural products. The share of the agro-industrial complex including the agriculture and processing sector is 8.9 % of the gross regional product. The natural and climatic risks form constant threats for stability of agricultural production volumes and precondition high expenses of producers.

According to the integral soil quality assessment for agricultural use performed in 2013, the Krasnoyarsk Territory is related to the “most unfavourable” regions [7]. The percent of soils unsuitable

for agrarian production is 81. The area of the most fertile and respectively most productive soil in agriculture — the black soil, as compared to the total area, is insignificant (about 1.9% in total). However this percent corresponds to approximately 4.44 mln ha — a huge area, thanks to which the Territory is one of the main producers of food and commercial grains in Siberia. The area of sod-carbonate and grey forest soils, also suitable for profitable arable farming, is more than four times larger. Agricultural production is conducted primarily on the most fertile and profitable soils requiring less costs for processing, fertilization and means for plants protection.

The studies of long-term climatic indicators at the Krasnoyarsk Territory showed that the annual mean air temperature has grown during the recent 100 years by 1.44 °C at the trend equal to +0.0145°C/yr and the annual mean sum of precipitation grew by 82.4 mm at the trend of +0.83 mm/yr. Between 1976 and 2018 the trend was + 0.47 °C/10 years [1]. During the recent 40 years mainly positive air temperature anomalies [2] have been noted, which speaks to the intensive temperature increase of surface air as compared to the previous periods (table 1).

Table 1. Rate of increase of mean annual air temperature (linear trend) for natural zones of the Krasnoyarsk Territory [1].

Region	Linear trend for 1976–2018	
	Mean annual temperature, °C/10 years	Trend contribution to dispersion (D %)
Krasnoyarsk Territory	0.47	29
Tundra	0.85	53
Forest-tundra	0.63	31
Taiga	0.4	16
Forest-steppe	0.25	10
Steppe	0.26	9

The quantitative estimates of linear trends testify to warming in all latitudinal natural zones of the territory. The distribution of values of the linear trend coefficient indicates that most intensive increase of the temperature occurs in tundra and forest-tundra. The corresponding values of the linear trend coefficients are 0.85 °C and 0.63 °C/10years. Air temperature increase in steppe and forest-steppe zones occurs more slowly (0.26 °C/10 years). During the recent 50-years' period increase of the annual sums of precipitation by more than 30–50 mm/yr has been noted in the steppe, forest-steppe zone and in the zone of mountain and taiga dark-coniferous forests and middle taiga.

Change of climatic parameters at the Krasnoyarsk Territory occurs with a higher speed than on average for the whole RF territory. The most probable forecast of climate change until 2050 assumes global climate warming by 0.6–0.7 °C and then by approximately 1.7 °C; also, the amount of precipitation will grow by 30–50 mm/year.

It becomes evident that, as the result of climate changes and their influence on the environmental components, shifting of forest and steppe landscapes occurs. In the Holocene optimum when the air temperature was 3–4 °C above the current one, shifting of the forest-tundra border to the north within Western and Middle Siberia made 250–300 km as compared to the current position [8]. We think that the predicted warming by 0.6–0.7 and then approximately 1.7 °C will shift the northern border of the forest-tundra by 50–135 km. Shifting of all natural zones will occur to the north with occurrence or expansion of transitional landscapes, but it will occur less distinctly. The borders of zones can shift at tens of kilometers.

Climate changes observed during the recent 30 years assist in the growth of potential efficiency of agriculture at a significant part of the Russian Federation, where at least 85% of agricultural products

are produced [9]. Meanwhile, the growth of climate aridity is observed at some areas of Siberia, leading to decrease in the agrosphere efficiency.

Based on the expert estimates it can be predicted that transformation of soil and land resources of the Krasnoyarsk Territory will occur at the species, generic and subtype levels. Within the natural zones zonal and provincial soils will preserve, and their changes will be minimum. In transitional areas and areas of natural zone border shifting replacement of one type of soil with another one is possible.

At the areas neighbouring sea coasts, increase of the water level (presumably by 15–20 cm) is possible, which will increase the bogginess of lands and the area of hydromorphic soils. At the area of the cryolithic zone degradation of permafrost will continue, as the result of which the area of bogged soils in tundra and the taiga zone will increase. Meanwhile, as the result of loss of the shielding role of the permafrost, drying of some soils is possible. Thawing of permafrost will lead to pedoturbations and mixing of the soil mass. A part of humic and peat horizons will shift to the lower part of slopes. The podzolization process will intensify and expand on light soils.

The ratio of sod-podzol and podzol soils will change in southern taiga in favor of the first ones. When the southern taiga border shifts to the north, sod-podzol soils will be replaced by grey forest soils. Even now, it is very hard to diagnose morphological differences between these types. Natural drying of bogs and degradation of the peat stratum will occur. The value of a subzone in agricultural production will grow.

In southern taiga and northern forest-steppe the process of humus accumulation will intensify. We think that the increase of the humus content in soils will occur as per the conditions of moisture and heat supply in accordance with the model as follows:

$$\text{Humus, \%} = -20.3080 + A \cdot 0.0205 + B \cdot 0.1349 + C \cdot 0.0237$$

where, A is the sum of precipitation for the period with the temperature over +10 °C, mm; B is the period with the temperature over +5 °C, days; and C is pure primary products of agrocenoses (NPP), dt/ha.

The model has been received on the basis of studying the dependences between the humus content in arable soils and indicators of moisture and heat supply, as well as the values of the primary products of agrocenoses. The presented model is applicable within the following maximum and minimum values: the sum of precipitation for the period with the temperature over +10 °C — 146–257 mm; period with the temperature over +5 °C — 134–159 days, and NPP — 26–137 dt/ha. The communication between the independent variables and the humus content is linear, therefore, in the specified value range humus accumulation in soils will occur.

In the forest-steppe the ratio of black soils, meadow-black soils and grey forest soils will change. Meadow-black soils and dark-grey forest soils will be diagnosed as clay-illuvial black soils. The content, reserves and composition of humus will most probable remain the same on noncropland. The soils under the crop land will undergo further dehumification. On a part of crop land massifs the thickness of the humus horizon will decrease. With the decrease of the humus horizon below 20–22 cm ploughing of soil forming rocks will occur. Cropping out to the day surface and supply in the humus horizon of Later Pleistocene high-carbonate rocks of the Sartan suite will worsen the soil properties abruptly and will lead to reduction of their fertility and agricultural value.

In summer the water reserves in the meter layer of these soils will remain the same, thanks to the increase of precipitation. Bog massifs will disappear, and the peat stratum will be intensively mineralized. The area of steppified sections will grow, where the degree of soil alkalinity will increase.

Drying of soils will intensify in steppe landscapes. According to the model comprehensive forecasts, if the current level of agricultural engineering and geographical distribution of crops is preserved, the fertility of crop cultures will fall by 20–25% to the middle of the 21st century [11]. The area of lands exposed to deflation processes will grow. The soil dehumification process will intensify. The development of irrigating infrastructure will be required in steppe landscapes, without which it will be impossible to perform economically profitable arable farming. Without irrigation, the considerable part

of arable lands can be used only as low-productive pastures. In the forest-steppe zone it will also be required to significantly expand the areas of irrigated lands. This measure is most efficient at floodplain soils, the economic value of which, thanks to the nearness of water sources and soft microclimate, will grow abruptly. Shortage of nutrient elements of plants will be the second factor limiting fertility, which requires the use of mineral, primarily nitric and phosphoric fertilizers.

It is necessary to take into account the fact that the anthropogenic influence on soil and land resources will be more intensive than that of natural changes. The probability of occurrence of process soil degradation, erosion, alkalization and salination, desertification, droughts and fires will increase. The southern natural border of the forest will shift to the north. In these conditions the environmental wellbeing of landscapes and soil and land resources will be defined by the level of development of intellectual and production forces of the society.

As the result of bog drying (the degree of boggingness of the forest-steppe zone is 5%) considerable massifs of soils suitable for agricultural use will be involved in the turnover. Also, significant areas (about 1 mln ha) of fallow lands, where intensive replication of natural zone biogeocenoses and recovery of the humus condition of soils and reserves of nutrient elements of plants occurs, shall be involved in the turnover.

The efficient use of soil and land resources is real in the conditions of economic support from the state. The formation of new and reconstruction of old irrigating systems, provision of food producers with mineral fertilizers and means for plant protection (also against locust invaders), the use of modern drought-resistant cultures and sorts, introduction of modern moisture preserving technologies of arable farming will require significant capital investments. Climate warming accompanied by the increase of summer and winter precipitation, milder winters and extension of the vegetation period is favourable for a wider spectrum of agricultural cultures and sorts, passage of phenophases of plants, will have a general positive impact on the development of commercial arable farming in the region, especially in the forest-steppe zone.

3. Conclusions

The quantitative estimates of linear trends testify to warming in all latitudinal natural zones of the territory. The forecast of climate change until 2050 assumes global warming of climate by 0.6–0.7 °C and then by approximately 1.7 °C; also, the amount of precipitation will grow by 30–50 mm/year.

As the result of climatic changes and their influence on environmental components shifting of natural zone borders to the north and occurrence or expansion of transitional landscapes occurs. The assumed warming will shift the northern border of the forest-tundra by 50–135 km. Shifting of the borders of other natural zones will occur less distinctly, by approximately tens of kilometers, which will lead to transformation of soil and land resources.

The transformation of soil and land resources of the region will occur at the species, generic and subtype levels, and rarely one type of soil will be replaced by another one. In the forest-steppe the ratio of black soils, meadow-black soils and grey forest soils will change. Meadow-black soils and dark-grey forest soils will be diagnosed as clay-illuvial black soils. The soils under the crop land will undergo further dehumification. Improvement of climatic conditions in general will have a positive effect on the development of commercial arable farming in the region, especially in the forest-steppe zone.

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